Power Flow Optimization with Energy Storage - Sal Island Case Study

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Abstract: - The correlation between energy costs and the country's economic competitiveness is an unquestionable reality also responsible for the improvement of the population's life conditions. In the past Cape Verdean electric power system (EPS), expansion was based on fossil-fuel power plants, nowadays it shifted to renewable energy (RE) which is abundant in the Cape Verde archipelago. However, no reduction in the electricity tariffs occurred, due to renewable curtailment and other pendent questions related to power transmission losses in the EPS.

This paper presents an approach, that supports an implementation of a distributed electric energy storage system (ESS) on the Sal Island of Cape Verde archipelago, as a solution to increase the RE integration and power Transmission congestion relief. Thus, a power flow optimization is only achievable by storing excess RE as near as possible to consumption buses that can reduce overall transmission losses. The most advantageous allocation of ESSs along the EPS buses is combinational which faces a maximization of transmission loss reduction and minimization of ESS investment capital. The proposed tool to manage the "trade-off" between cost and avoided losses, is based on a genetic algorithm (GA) that is broadly applied to multi-objective problems like this.

Key-Words: - Distributed Generation, Power Flow, Renewable Energy, Curtailment, Genetic Algorithms, Energy Storage.

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1 Introduction

The EPS of Sal Island is this paper's case study object because it is one of the most expanding energy systems in the archipelago which also was followed by a growth of power transmission losses. Furthermore, a large portion of wind energy available in the island's Wind Power Plant is curtailed since the peak consumption that usually doesn't match with the existing Wind Power Plant peak production, which is unfeasible because the Diesel Power Plant minimum production must represent at least 50% of the production mix to ensure grid stability and spinning reserve.

Electricity production costs on the island depended on the fossil fuel importation costs, which had led to high susceptibility and dependence on international events. After an increase of 30% in energy costs from 2005 to 2009, following Brent's increasing price, the government initiated a baseline plan for RE in Cape Verde, to obtain Sustainable Energy from an economic and environmental point of view. To solve this situation a Solar Power Plant and Wind Power Plant were installed on the island and began operating, increasing endogenous production as defined in a document titled "*Plano de Energias Renováveis de Cabo Verde-2011*", [1].

When the RE power plants started operating Sal´s EPS began to have some stability problems and couldn't absorb all ER produced, which is why curtailment started to assume values above 40%, that's why this papers case study is focused on the use of ESS to improve RE integration. At the same periods of consumption present in the load diagram, ESS helps reduce power flow between generation buses and load buses, by providing energy discharging next to the consumption distribution buses.

Some advantages of the ESS implementation on the island are not accounted in this paper, which is stated as follows:

- Electrical network Investment Deferral (Cables and transformers);
- Better use of land disposable to RE plant´s operation;
- Improving RE plants life cycle and producing energy.

Typically the companies responsible for the sizing and location of ESS on the grid, do not take into account reduction in power losses, they usually locate da ESS nearby the RE source (Wind Power Plants or Solar Power Plants) or near consumption as an efficient way of storing energy, but some researchers look to the grid as an all, trying to allocate the best size ESS units that guarantee technical and economic stability of the grid. As examples we can see the following two articles:

The authors in, [2], have shown that a multi-objective multiverse optimization method (MOMVO) is used as a solution tool for optimal allocation and sizing of ESS in Power Grids to improve the voltage profiles and minimize the annual costs, as result a Pareto optimal solution set is minimized under economic concerns and cost sensitivity to provide a decision-support for the utilities. In, [3], is proposed a three multi-objective algorithms of particle swarm optimization (PSO), variable constants (VCPSO) and genetic algorithm (GA), the main objectives of this solution tool are to detect the optimum size and location of multiple ESS aiming to reduce active power loss and improve bus voltage deviations in the distribution networks.

In this context, this paper presents an approach, that supports an implementation of a distributed electric energy storage system (ESS) on the Sal Island of Cape Verde archipelago, as a solution to increase the RE integration and power transmission congestion relief. Thus, a power flow optimization is only achievable by storing excess RE as near as possible to consumption buses that can reduce overall transmission losses. The most advantageous allocation of ESSs, and selecting their best size capacity along the EPS buses is combinational which faces a maximization of achieved transmission loss reduction and minimization of ESS investment capital. The mathematical model herein proposed involves both discrete and continuous variables as well as nonlinear constraints, namely related to power flow equations. Therefore, due to the presence of multiple objective functions, non-linear relations, and its combinatorial nature the model is hard to solve using mathematical programming algorithms. This was the motivation to resort to GAs to compute non-dominated solutions to the model developed, [4], [5].

2 Sal Island EPS Characterization

Sal Island is located on the Northeast of the archipelago, with a total area of 220km^2. There is approximately 30.000 inhabitants, distributed along the four places (*Espargos* - main local residential and administrative city, *Santa Maria* - touristic center, *Palmeira* - port and fishing town, *Pedra Lume* -fishing village). The electricity needs of Sal Island is approximately 72GWh per year. This amount of electricity is provided in 67,4% by the Diesel Power Plant of *Palmeira* town and Wind/Solar Power Plants that represent 27% and 5,6% of the energetic matrix respectively), [6].

Electra a state owned company is the EPS concessionary, that operates *Palmeira´s* Diesel Power Plant whit 12MW of installed power capacity to provide energy security and required a spinning reserve to absorb RE intermittency. The concessionary also operates a Wind Power Plant with an installed capacity of 3x1,6MW. As concluded in a RE assessment, it was strategic to construct a 2,5MW Solar Power Plant on Sal Island in a strategic place reserved by law as a Renewable Energy Development Zone (ZDER), [1], [7].

Electra follows energy sector directives defined by the local State Agency for Energy, which currently encourages the entry of private initiative on the EPS, while seeking to solve *Electra´s* poor financial performance, caused by elevated technical and commercial losses and slow technologic transition influenced by fuel oil (180 to 380 heavy fuel) volatile prices.

The electricity price is regulated by the Economic Regulation Agency (ERA), which is responsible for balancing the interests of consumers and producers, [8], [9].

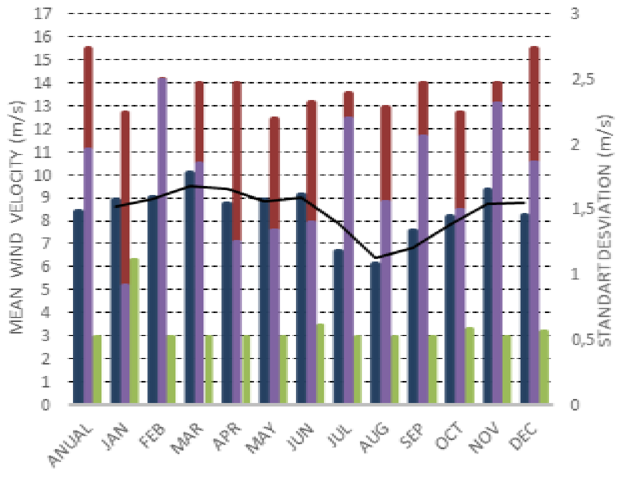


Fig. 1: Yearly wind availability and statistics on Sal Island, 2018.

The Islands plan morphology concedes a low spatial variance of wind availability, but still land-use is environmentally concerning and restricted by the aeronautic hub. As shown in Figure 1, wind temporal availability is constant, having a small seasonal sag from June to November, studies suggest 2700 equivalent full load hours, [10]. The highest wind availability is registered between 6PM-7AM night-time period.

Sal Island´s Wind Power Plant is operated by *Caboéolica* a company formed from a public-private partnership. The energy is bought by *Electra* at a cost of 0,14€/kWh in a “take or pay “signed contract, [11].

Sal Island electricity consumption doesn´t vary much over a year period, due to a diversification and expanding tourist market activity, which is levelling the Island’s energy consumption and due to a very stable weather factor.

3 Overview of Storage Technologies

The main technologies to store electric energy are based on converting it into a storable type of energy (mechanical, thermal, electrochemical), so it can be used later using a mechanism to reconvert it back on electricity. The main characteristics that define the best sights and strategies where a specific type of ESS can be applied in EPS are: specific power/energy, volume/density, charge/discharge rate and life cycle, [8], [12], [13].

Mechanical storage like Reverse Pumping, Flywheel or Compressed Air Energy Storage (CAES), is based on converting electric energy into gravity potential, rotational inertial or elastic potential energy, respectively, [14]. CAES and Reversed Pumping are more profitable on large scale Power solutions where large quantities of energy can be stored and used for a long period of time, usually these technologies have geological and geographic installation restrictions. Flywheels are more intended for fast power response, commonly used for energy quality, which is very useful for stabilizing the start-up of RES.

Electricity can also be stored in an *electrostatic filed* between two plates inside a double layer capacitor (Super Capacitors) or in a *magnetic field* in a cryogenically cooled super conducting coil (SMES-Superconducting magnetic energy storage), [15]. These two Electric storage technologies are used in EPS when a huge amount of power is needed in a very short time period, often used in research facilities or to compensate large industrial machinery voltage fluctuation caused by their operation (ex: cranes, arc forge, etc.).

Thermal energy storage can be done in cryogenics or heat which are typically associated to three types of technologies depending on the heated material, defined as: Sensible Heat, increases temperature of a mass; Latent Heat, storage takes advantage of the energy absorbed or released during a phase change and thermochemical energy storage, uses the heat absorption of a chemical reaction. Practical applications of Cryogenics EES are achieved by liquefying air or cooling water, [16]. Thermal ESS is usually cost-effective when employed directly on HVAC or when energy is very cheap like in electricity from nuclear Power Plants or from RES surplus energy, [17].

Electricity is stored *electrochemically* in Batteries whatever their chemistry (aqueous, no aqueous, Li or Na-based) within the electrode structure through charge transfer reactions (oxidation-reduction), [18], [19]. In Other way, Fuel Cells, store energy in the reactants that are externally fed to the cells during the discharge process, [20], [21]. Both of these differ from redox-flow cells, which store energy in the redox species that are circulating in a closed circuit through an electrochemical cell, [20], [22].

Based on this description, different ESS can be applied to the EPS to improve its operational parameters caused by the variability of loads and RES. So according to their characteristics some technologies are used in:

- *Power quality* - provides electrical service to EPS during oscillations or disruptions to the waveform such as swells/sags, spikes, or harmonics;
- *Power bridge* – ESS discharge in a short period of time while the main source (thermic, hydro

or nuclear) is rising up or being set in grid synchronization;

- *Energy Management* - curtailed price of excess energy produced at night can be used during peak demand periods during the day time. This allows arbitraging the production price of the two periods and a more uniform/leveled load factor as exemplified in Figure 2.

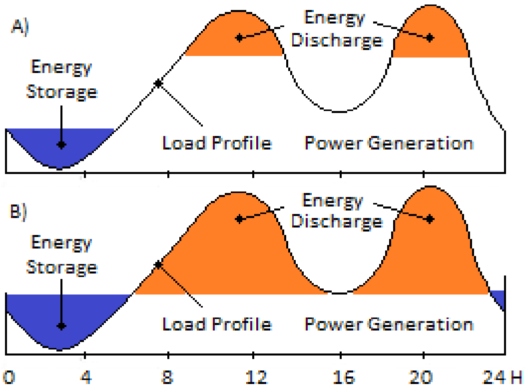


Fig. 2: Energy management is done by ESS; A) peak shaving and B) load leveling.

The ESS technology most used in islands EPS the size of Sal Island are ESS using lithium batteries.

Some examples of this kind of implementations, are:

- *Canary archipelago* - Grand Canary island, 1MW/3MW lithium-ion ESS, [23];
- *Azores archipelago* – Graciosa Island 7,4MWh/3,2MW lithium oxide titanium ESS, [24].

In these examples typically to level a 2-hour peak consumption the ESS size is suited in an energy/power ratio of 2:1 and the charging is done at night-time to avoid an increase on power flow that results from the most abundant renewable power excess period. Figure 3 presents an ESS container topology based on lithium-ion batteries.

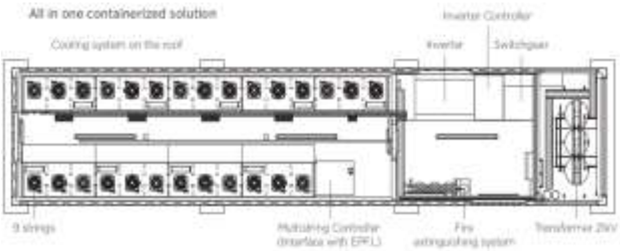


Fig. 3: Energy Storage System based on a container string 9 strings 15 modules each, 700V 90Ah whit 63kWh.

Lithium battery ESS are used in these situations because they have high reliability and low maintenance and exploitation costs compared with other batteries (Lead-Acid, NAS Flow, Zinc Air), they have a bigger life cycle, specific power and energy (including density), which makes them a very interesting solution for island located installations with low technologic Know-how.

4 Multi-objective Problem Optimization

The problem of finding the optimum location and sizing ESS distributed along the EPS can be stated as a multi-objective planning problem. In fact the solution space is large, combinational, and nonlinear where the fitness of each solution is analyzed to guarantee that only strong solutions prevail, [25]. A multi-objective method handles on a Pareto Front (PF) display where it has the capability to give a better understanding to the decision-makers (DM) for selecting good compromise solutions having in mind their economic and technical implementation. The PF, in our case study, is a frontier in the solution space where non-dominated solutions have the best trade-off between investment cost and avoided power losses.

Multi-objective problems (MOP) optimization relies on three classes of methods: enumerative, deterministic, and stochastic, [26]. The stochastic methods such as GA have a great computational performance and accessible implementation. It is a bio-inspired method, also called an evolutionary algorithm because its principles are based on evolutionary theory like cross-over, mutation and selection, which can be determinants of the survival of the more fit individuals in the next generation.

Genetic Algorithms basic concepts

Gene - each variable in the solution is designated as a gene usually coded in a binary, decimal, or grey; for easier data manipulation, [27].

Chromosome - an array of genes that represents a solution also designated as an *individuum*; the position in the array identifies the variable, [28].

Non-dominance - a non-dominated solution is defined as not having a solution with a better performance to optimize the problem. As illustrated in Figure 4.

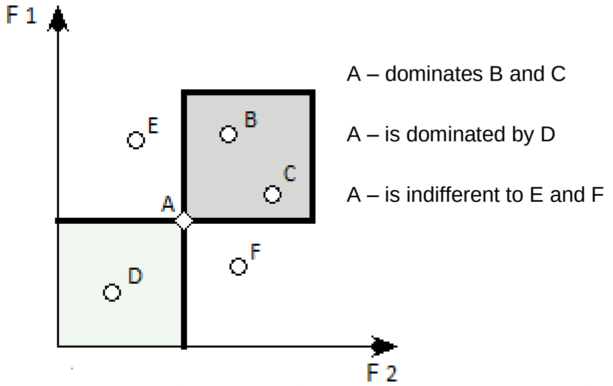


Fig. 4: Example of the dominance concept, used to define an *individuum's* fitness, on an AG implementation, [29].

Population – is formed as an array of chromosomes, each genetic operator along it´s iterations/generations creates a new population. There are special populations like the initial (P_0) that is created randomly, and the secondary population (P_S) used as an auxiliary place to save non-dominated solutions (P_{iter} - P.iteration and P_{cand} - P.candidate).

Mutation - genetic operator, that depending on the mutation probability changes a non-dominated variable randomly. It is correlated to population diversification but in high probability can decrease convergence, [29].

Crossover – is the combination between two fit solutions, creating a descendant that saves partially a portion of the genes of the two progenitors. The genes distribution in the new progenitor solution can be done according one-point, two-point splitting or another pattern. Crossover type and probability shape final population convergence performance, [26], [29], [30].

Elitism - highest performance solutions are subject to elitism, which prevent them from passing through other genetic operators (cross-over, mutation, selection) shielding them from possible degradation. High elite array increases population stagnation and can lead to local optimization solutions, [31].

Selection – to select *individuum's* to transit to the next generation/iteration. The used methods of selection can be: ranking, roulette wheel or tournament. The AG that uses the tournament selection, chooses randomly the best pair of *individuum's* to transit to the next generation, [29], [30]. Tournament selection preserves population's diversification and is low computationally demanding, [25], [32].

Robustness - practical implementation cannot be done with ideal material or no tolerance on the performance specification, also they are subject to external variables non-accounted in the modulation. A robust solution is defined as having a low deterioration, when induced to disturbances. The GA considers a solution with a high degree of robustness when it is necessary in a distant radius of simulated disturbance on input variables centered from the considered solution, to decrease the solution fitness in a determined radius from the initial output fitness, [25], [32].

Sharing - it´s applied when $NP_S > NP$, after solutions with the best values in each objective function (F_n) are inserted into the elite population then, a dynamic niche is computed ($ds = Maxdistance(F_1, F_2)/NPs$) and all the solutions at a distance greater then *ds* from the ones already belonging to the elite are inserted. If Ps remains unfilled, it will be dynamically adjusted until the population has the predefined size NPs, [25], [29].

A lot of AG variants are presented and discussed in academic papers, in this paper we focused on NSGA II (non-dominated sorting genetic algorithm) as it grants fewer disadvantages than other approaches, and also it seems to have a great rated performance on testing MOP, [29]. NSGA II application is expressed in Figure 5.

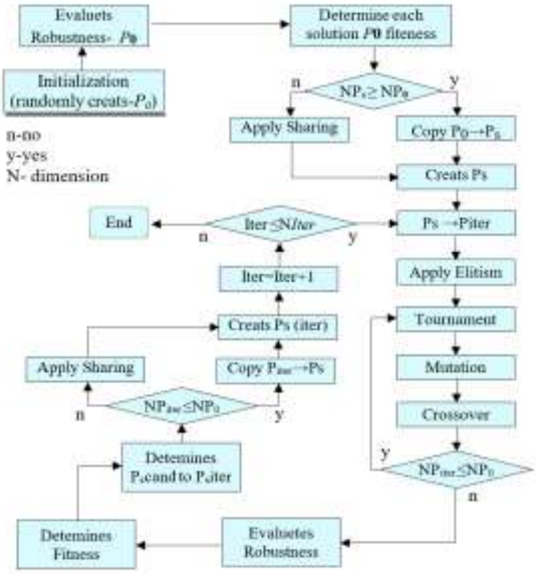


Fig. 5: Flowchart of the applied AG on multi-objective problems, NSGA II, [25].

5 Distribute ESS Problem Formulation

This paper presents a problem of optimal placement and sizing of ESS units on Cape Verde Islands EPS where two objective functions are considered: minimizing installation costs and minimizing system losses. The used constraints are related with service quality (bus voltage profile), networks physical laws (obtained by power flow analysis) and some technical restrictions (impossibility of installation of certain ESS units at certain buses).

The result of the formulation expressed below, represents a simplified notion of avoidable losses that can be obtained by reducing power flow between production and consumption buses. As peak consumption increases DM usually increases the network capacity or invests in distributed generation to achieve loss reduction.

The major goal of this approach is finding, a solution based on distributed storage, in order to reduce transmission losses and at the same time RES curtailment.

Thus, the implemented layout of the distribution of ESS on the grid, should be formulated, regarding to:

Minimize (min) [Cost $_{\text{installed storage}}$; Power $_{\text{losses}}$]

Subject to $(s.t)$ *Power flow Equations*
V, I Limits
PT power and space limitations

Installation costs are given by equation (1),

$$min\sum^{\alpha}\sum^{\beta}\sum^{\kappa}\left[\sum^{\gamma} a^{k}_{\gamma\,\alpha\beta}.C\,\gamma\right] s.t. \sum^{\gamma} a^{k}_{\gamma\,\alpha\beta}.1, \forall\, \alpha,\beta,\kappa \quad (1)$$

where, $a^{k}_{\gamma\,\alpha\beta}$ represent the binary decision variables, that determines if a ESS can be installed in a certain bus and $C\gamma$ is its acquisition cost, γ is its storage capacity, α is the index related to a bus in a secondary branch, β the branch identification and κ the index of a bus number in the main branch.

The power losses minimization is given by equation (2),

$$min\sum^{\alpha}\sum^{\beta}\sum^{\kappa} r^{\kappa}_{\alpha\beta}.\frac{(Pc^{\kappa}_{\alpha\beta})^2+(Qc^{\kappa}_{\alpha\beta})^2}{(V^{\kappa}_{\alpha\beta})^2} \quad (2)$$

where, $Pc^{\kappa}_{\alpha\beta}$ and $Qc^{\kappa}_{\alpha\beta}$ are the corresponding active and reactive power flow between the buses caused by the resistivity $r^{\kappa}_{\alpha\beta}$ of the power cable.

Power flow (active/reactive) between buses in a secondary branch is given by equation (3) while equation (4) refers to power flow on the main branch, both depend on $Pg^{\kappa}_{\alpha\beta}$ power generated locally in the bus.

$$P^{\kappa}_{(\alpha+1)\beta}=P^{\kappa}_{\alpha\beta}-r^{\kappa}_{\alpha\beta}.\frac{(Pc^{\kappa}_{\alpha\beta})^2+(Qc^{\kappa}_{\alpha\beta})^2}{(V^{\kappa}_{\alpha\beta})^2}-Pc^{\kappa}_{(\alpha+1)\beta}+Pg^{\kappa}_{(\alpha+1)\beta} \quad (3)$$

$$P^{0}_{\alpha\beta}=P^{0}_{\alpha\beta}-r^{0}_{\alpha\beta}.\frac{(Pc^{0}_{0\beta})^2+(Qc^{0}_{0\beta})^2}{(V^{0}_{0\beta})^2}-Pc^{0}_{0(\beta+1)}-\sum_{\beta=1}^{B}P^{(\beta+1)}_{0\beta}+$$
$$Pg^{0}_{0(\beta+1)}, \forall\, \alpha,\beta,\kappa \text{ being B= number of branches} \quad (4)$$

Equation (5) defines how voltage can be determined for a given bus, while constrains (6) ensure that energy quality in EPS is between acceptable intervals defined by legislation.

$$V^{\kappa}_{\alpha\beta}=V^{\kappa}_{(\alpha-1)\beta}-\left(X^{\kappa}_{\alpha\beta}-r^{\kappa}_{\alpha\beta}\right).\left(\frac{(Pc^{\kappa}_{\alpha\beta})+(Qc^{\kappa}_{\alpha\beta})}{(V^{\kappa}_{\alpha\beta})}\right) \quad (5)$$

$$\max(V)\geq V^{\kappa}_{\alpha\beta}\geq \min(V) \quad (6)$$

In addition to the constraints of physical nature related to the load flow equations, another considered constraint (7) is the limitation imposed that at most one ESS unit can be placed in each bus.

$$\sum^{\gamma} a^{k}_{\gamma\,\alpha\beta}.\leq 1, \forall\, \alpha,\beta,\kappa \quad (7)$$

Based in historical electricity data, for this case study, the peak consumption is assumed as 10,2MW, this value is taken from the most statically representative month (July) sampled from 2018.

Sal Islands EPS distribution MV grid simplified diagram is presented in Figure 6, as can be seen demand peak loads are dispersed over buses as its corresponding transformer capacity in each community location, resident population and touristic places.

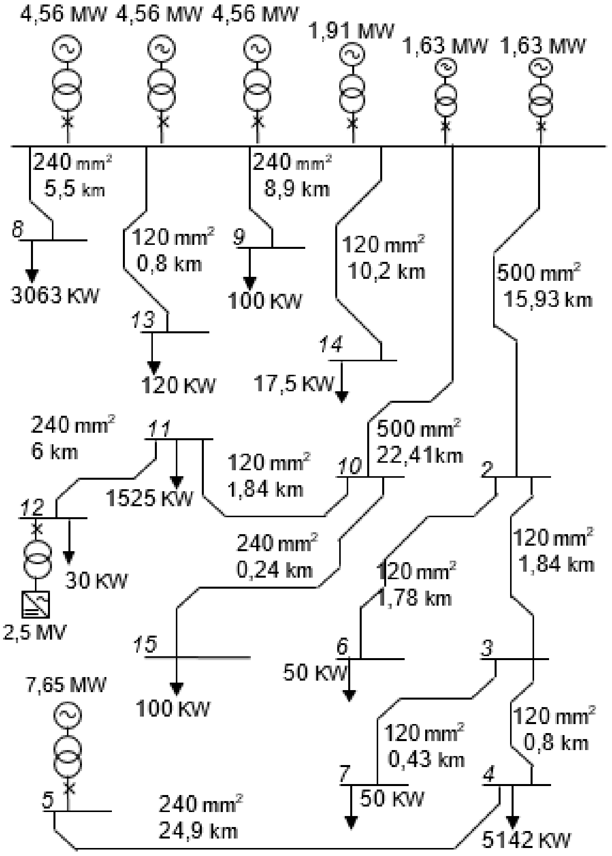


Fig. 6: Sal Island simplified MV network, taking load distribution formulation using transformer post capacity and a statistic consumer assumption.

The MV, 20kV, distribution grid is installed underground in a star/radial topology. The main branches have their starting point at the Diesel Power Plant and ends on the RES generation buses. Mainly, used cables are identified by LXHIOAV with 120-240-500mm^2 depending on the distance and load. Two parallel cables go to bus 4 (Santa Maria) which is divide in two but explored as an open ring topology. All derived buses on the way have a sectioning station connecting both cables, guaranteeing the insolating of faults and power flow transfer to the outer cable, improving reliability. Being an underground grid, it creates a capacitive effect (Ferranti effect) so reactive won´t be accounted, [33].

Peak-hour transmission losses represent about 6-7% of annual losses. The Sal Island EPS annual power losses are responsible for technical and commercial losses of about 280.000€ every year; losses costs are paid by the consumer through a tariff compensation parcel. *Electra* undertook yearly submission of a Loss Reduction Plan to ERA, thus ESS can be used as well for RES integration.

6 Case Study

Wind energy curtailment is a long-standing issue on Sal´s Island EPS, yearly it represents an average of 40% of the energy generated in the Wind Power Plant as shown in Table 1. The curtailment causes can be summarized by the oversized Wind Power Plant installed capacity, made to anticipate an energy consumption growth that didn't occur; possibly due to implementation logistics, to dilute fixed engineering cost and project scale price influence was greater than the oversizing cost.

Table 1. Wind energy curtailed vs. Wind farm availability and used energy wind energy, between 2013 -2018 on the Sal Island network.

	2013	2014	2015	2016	2017	2018
Used wind energy						
GWh	16.5	16.6	18.8	17.2	16.6	19.4
Curtailed wind energy						
%	N.A	N.A	47	48	46	42
Wind Power Plant availability						
%	99	99	99	99	99	99
Wind farm contribution to EPS mix						
%	31	33	32	31	27	22

Also spinning reserve is not sufficient to integrate all the wind energy available and it isn't economically viable for the EPS concessionary to buy energy from *Cabelólica´s* high values contractually defined. *Electra* tend to minimize wind energy purchases, exploit low fuel market prices and maximize its thermal capacity use to repay its investment.

Regarding the power transmission losses, the Island´s grid peak hour (19-20h) losses including only MV cable represent 6-7% (~16k€) of the global energy losses (~240k€/ 2% of produced energy), which are accounted to the energy selling price.

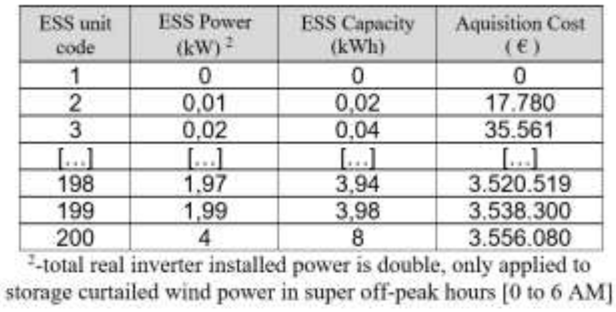
Every five years, regulation obligates the concessionary to reinvest a share of its profit, in an energy losses mitigation plan which can create a synergy between losses reduction and wind energy integration, using an optimal ESS distribution on the Island, [34].

The GA configuration

The GA methodology, described in section 4, should receive input from a ".txt" file that describes the EPS configuration and the available market solution, so the algorithm can be able to interactively generate (ESS allocation) and evaluate (avoided losses/cost) a solution/*individuum*.

Electric data is stored in a matrix form, in which columns divide them by types (resistance, start bus, end bus, number of derivations, loads, generation) and lines by a branch or bus index/code. Table 2 exemplifies some ESS solution codes and characteristics inserted in the GA.

Table 2. Solution ESS power and its acquisition cost codification used by the GA, arranged in 20kW step corresponding to 17,7K€ steps.



ESS unit code	ESS Power (kW) [2]	ESS Capacity (kWh)	Aquisition Cost (€)
1	0	0	0
2	0,01	0,02	17.780
3	0,02	0,04	35.561
[...]	[...]	[...]	[...]
198	1,97	3,94	3.520.519
199	1,99	3,98	3.538.300
200	4	8	3.556.080

[2]-total real inverter installed power is double, only applied to storage curtailed wind power in super off-peak hours [0 to 6 AM]

ESS installation and operation best practice

Regarding the Diesel Power Plant management, it is relevant that it limits ESS on Sal Island life cycle between 30-50%, [35], so some suggestions to overcome this, are:

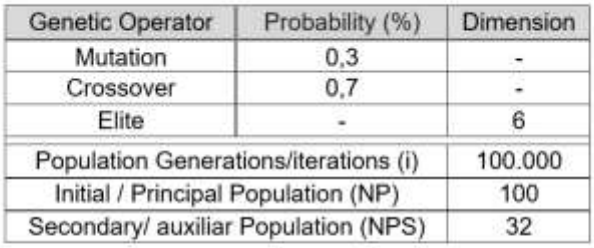
- inverters need a configuration to avoid batteries from overheating (eg: outdoor installation);
- use a PID (proportional, Integrative, derivative) analyzed ratio of stored/colling energy when curtailed wind energy is greater than storage capacity;
- use a predictive curtailment forecast management to avoid charging on nominal installed power.

To optimal enclosure of ESS in the grid, we need to take into consideration the best place to install it, so when feasible, the ESS should be installed inside a concrete transformer substation empty space or as close as possible to the substation LV bus container or concrete building. The LV integration of the ESS must be supported by a technical study, which considers, the LV substation´s empty space, load diagram, and ventilation upgrade, in order to avoid overload when the ESS is charging, personal risk, and cost reduction. ESS allocation on the LV grid can use the same allocation method as in the MV, not intended in this paper.

The GA operator parametrization analysis

As a non-deterministic method used in this case study GA operators are adjusted experimentally. Being a small multi-objective problem, the computational power processing required is low about (15 minutes/100.000 generations). The best parametrization is shown in Table 3.

Table 3. AG genetic operator, populations, and iterations, best suited to find optimized ESS allocation.



Genetic Operator	Probability (%)	Dimension
Mutation	0,3	-
Crossover	0,7	-
Elite	-	6
Population Generations/iterations (i)		100.000
Initial / Principal Population (NP)		100
Secondary/ auxiliar Population (NPS)		32

Operator adjustment guidelines were based on papers, which state, [29], [32]:

- Exclude domination and non-feasible *individuum* on the initial population;
- Crossover as the main operator since it is less stochastic;
- Mutation probability in an interval that avoid random search or population stagnation;
- Elite population enough to protect good solution degradation.

Crossover method analysis

As mentioned before crossover is the main operator used by the GA for the optimum solution convergence. Thus it´s important to analyze the crossover method's influence on the optimum solution convergence.

From Figure 7, we can conclude that Pareto convergence is influenced by the crossover method.

Meanwhile, uniform cut and 2 cut-off methods are more likely to distribute genes between the two halves of the chromosome in the copy of the genes to the descendant. The distributed copy of the genes along the chromosome of the descendant, or damage good solutions or improve the worst solutions, this means that it increases intermediate solutions.

The possible explanation for the best convergence of the one point cut-off crossover method may be that, when copying the chromosome of the parents from two halves, it guarantees a greater probability for the descendant to conserve the genes related to the installation of the ESS concentrated in the first half of the grid buses [bus 1 to bus 8] in which these buses represent the majority of the losses of the ESS (80%) and in the second half buses [bus 9 to bus 15] receiving little or no ESS installation, which allows a reasonable performance to the descendant.

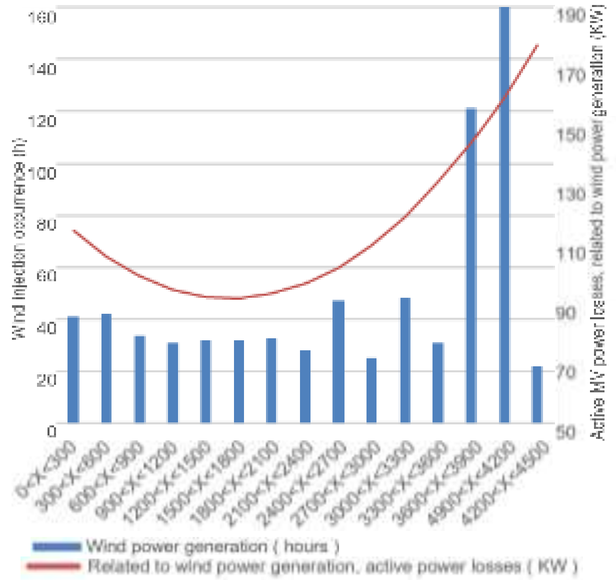


Fig. 7: Crossover method influence analysis over optimization gains.

RES variability compensation

Since the load distribution across the MV network was assumed as fixed for modeling purpose based on a statistic approach, to reflect the variability of the Wind Power Plant, an energy injection scenario method in (bus 5) is best suitable, overall it allows to simplify the ESS gains effect.

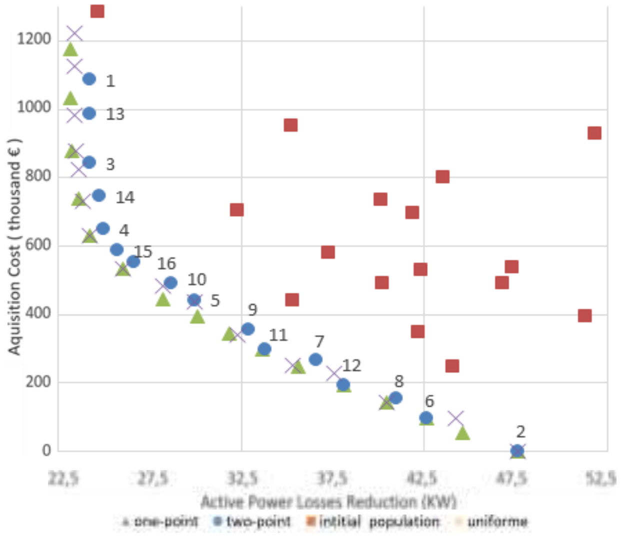


Fig. 8: Wind Power Plant production effect on total MV losses and observed Wind Power Plant hours of defined production power, in 300kW intervals.

Figure 8 shows the Wind Power Plant's influence on power transmission losses. To summarize all observed Wind Power Plant production conditions, quartiles are used as estimators to represent all sampled data, thus they sum the sampled values in three scenarios with statistical significance, as shown in Figure 9.

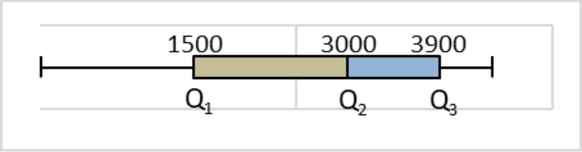


Fig. 9: Observed Wind Power Plant production quartiles, set on a whisker plot.

Scenario Q1 – 1500kW RES, analysis

As defined, scenario Q1 represents the first quartile of the sampled Wind Power Plant production (1500kW), which leads a 28% (37,1kW) losses reduction. Most of the losses, and decreases occurs between bus 1-[...]-4 due to the bidirectional feeding of bus 4 which represents 50,4% of the grid consumption.

Other branches aren´t affected by RES distributed production.

As a result, the last population found by the GA is a Pareto curve formed by a solution with big loss reduction/ investment cost ratio optimization.

Figure 10 shows the PF solutions obtained in scenario Q1 and its linear correlation coefficient as an optimization concavity/convergence optimization capability index.

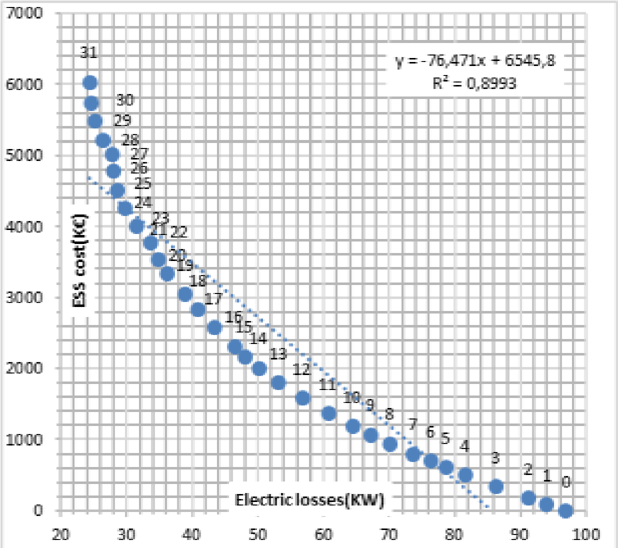


Fig. 10: Secondary population PF, computed by NSGAII for scenario Q1 -1500kW RES, along linear regression, and correlation.

It is visible that a reverse correlation between losses/investment costs, is expected in this kind of multi-objective problem. To notice solution indexes are rearranged in ascending order, to simplify analysis.

Solution Q1-N1 minimizes cost, where losses are reduced by 3% (2,9kW), corresponding to the installation of a 100kW ESS and 89.000€ investment.

In comparation solution Q1-N31 minimizes losses in 72%, which corresponds to the installation of a 6,8MW ESS involving 6.000k€.

Optimized *individuals* have host of the allocated ESS, on bus 4 which is the most energy-demanding and farthest from Diesel Power Plant.

Making a population chromosomic analysis from Table 4, in solution Q1-N16, we can see that bus 4 cannot alone guarantee both objective minimizations, so bus 8 turns out to be necessary. Bus 8 is a large consumption bus connected by a 120mm^2 cable, so is intelligible the appearance of this gene/ESS. The solution Q1-N17 appearance, may be explained by a similar minimization performance and/or due to genetic operator effort to maintain diversity.

Table 4. AG computed PF population chromosome matrix and performance for scenario Q1- 1500kW (1-losses kW; 2-cost k€).

Bus		1-3	4	5-7	8	9-10	11	12-15	L^1	C^2
Solution Index	0	0	0	0	0	0	0	0	96,9	0
	1	0	5	0	0	0	0	0	94,0	89
	2	0	10	0	0	0	0	0	91,2	178
	3	0	19	0	0	0	0	0	86,3	338
	4	0	28	0	0	0	0	0	81,6	498
	5	0	34	0	0	0	0	0	78,7	605
	6	0	39	0	0	0	0	0	76,3	693
	7	0	45	0	0	0	0	0	73,6	800
	8	0	53	0	0	0	0	0	70,1	942
	9	0	60	0	0	0	0	0	67,2	1067
	10	0	67	0	0	0	0	0	64,4	1191
	11	0	77	0	0	0	0	0	60,8	1369
	12	0	89	0	0	0	0	0	56,8	1582
	13	0	101	0	0	0	0	0	53,2	1796
	14	0	113	0	0	0	0	0	50,1	2009
	15	0	122	0	0	0	0	0	48,1	2169
	16	0	130	0	0	0	0	0	46,4	2311
	17	0	131	0	0	0	14	0	43,4	2578
	18	0	131	0	28	0	0	0	40,9	2827
	19	0	130	0	41	0	0	0	39,0	3040
	20	0	147	0	41	0	0	0	36,2	3343
	21	0	158	0	41	0	0	0	34,8	3538
	22	0	171	0	41	0	0	0	33,7	3769
	23	0	144	0	81	0	0	0	31,6	4001
	24	0	158	0	81	0	0	0	29,8	4250
	25	0	173	0	81	0	0	0	28,6	4516
	26	0	188	0	81	0	0	0	28,0	4783
	27	0	147	0	135	0	0	0	27,8	5014
	28	0	158	0	135	0	0	0	26,5	5210
	29	0	173	0	135	0	0	0	25,2	5476
	30	0	188	0	135	0	0	0	24,7	5743
	31	0	194	0	145	0	0	0	24,4	6028

Now analyzing the PF solutions economic performance, they correspond to a reduced watt loss per thousand € (W/k€) interval, between Q1-N1 32,8 W/k€ and Q1-N31, 12,3 W/k€. The middle solution or nearest to the interval average is solution Q1-N16, which makes it of course, the best trade-off on both objectives.

Scenario Q2 – 3000kW RES, analysis

Secondly, scenario Q2 shows an intermediate RES use situation (3MW), associated with the average of the sample.

As a result, losses are reduced by 16%, lower than in the Q1 scenario. Between buses 1-[...]-4 branches losses are lower, while losses between the Wind Power Plant (bus 5) and bus 4 increases by 60%.

Figure 11, shows the Q2 solutions present at the PF. After comparing Q1 and Q2, a linear regression slope coefficient (Q1.m= -76/Q2.m= -118), shows that the Q2 Pareto curve slope clearly reflects a lower avoided losses/investment cost ratio in comparison to scenario Q1. This happens because most of the losses between buses 4-5 cannot be reduced, by a distributed peak shaving ESS dispatch, but through a production leveling approach.

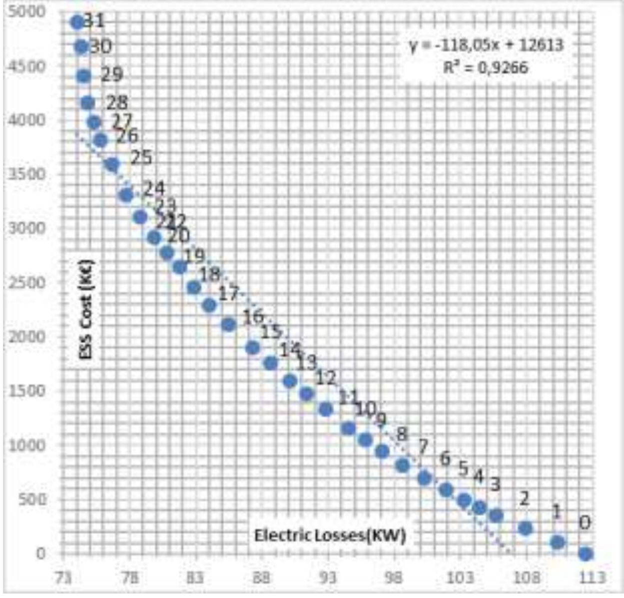


Fig. 11: Secondary population PF, computed by NSGAII for scenario Q2 - 3000kW RES, along with linear regression and correlation.

Incapability to reduce losses by allocating ESS along the branch 4-5, as shown in Table 5 creates a tendency to:

- Q2 PF starts early to host ESS in a dispersed approach (Between Q2-10 and Q2-15) on bus 11, also 3rd more responsible in power losses;
- after the Q2-N16 *individuum*, ESS solutions are more disperse and larger on bus 8, in comparison to the same interval from Q1 PF.

Besides technical analysis is important for the DM, an economic analysis, in this case, has fewer optimization gains as stated before. The scenario Q2 population have a ratio of W/k€, between 7,84 and 20,7. It is important to note that the reduction of RES is possible through the installation of larger ESS's, not accounted for in this analysis, but it has a great and positive influence on economic evaluation. Applying the same methodology to define the best solution used before, solution Q2-N14 evidently manages to have similar gains on both goals, as having a W/k€ nearest from the Q2 last computed population average (13,62W/k€).

Table 5. AG computed PF population chromosome matrix, Q2-3000kW (1-losses kW; 2-cost k€).

Bus		1-3	4	5-7	8	9-10	11-15	L¹	C²
Solution Index	0	0	0	0	0	0	0	112,5	0
	1	0	6	0	0	0	0	110,3	107
	2	0	13	0	0	0	0	107,9	231
	3	0	20	0	0	0	0	105,7	356
	4	0	24	0	0	0	0	104,4	427
	5	0	28	0	0	0	0	103,3	498
	6	0	33	0	0	0	0	101,9	587
	7	0	39	0	0	0	0	100,3	693
	8	0	46	0	0	0	0	98,6	818
	9	0	53	0	0	0	0	97,1	942
	10	0	53	0	0	0	6	95,8	1049
	11	0	59	0	0	0	6	94,6	1156
	12	0	69	0	0	0	6	92,8	1334
	13	0	59	0	0	0	24	91,3	1476
	14	0	66	0	0	0	24	90,1	1600
	15	0	75	0	0	0	24	88,7	1760
	16	0	64	0	43	0	0	87,3	1903
	17	0	76	0	43	0	0	85,4	2116
	18	0	75	0	54	0	0	84,0	2294
	19	0	84	0	54	0	0	82,8	2454
	20	0	95	0	54	0	0	81,7	2649
	21	0	79	0	77	0	0	80,8	2774
	22	0	87	0	77	0	0	79,8	2916
	23	0	96	0	79	0	0	78,8	3112
	24	0	95	0	91	0	0	77,8	3307
	25	0	92	0	110	0	0	76,7	3592
	26	0	105	0	110	0	0	75,7	3823
	27	0	103	0	121	0	0	75,3	3983
	28	0	108	0	126	0	0	74,9	4161
	29	0	122	0	126	0	0	74,5	4410
	30	0	109	0	154	0	0	74,3	4676
	31	0	122	0	154	0	0	74,0	4907

Scenario Q 3 – 3900kW RES, analysis

The last scenario is Q3, which refers to the upper/third quartile (3,9MW) of the observed wind energy injection, on bus 5.

In this scenario, losses increase by 7% when related to wind absence, in contrast to a higher RES power injection, from the Wind Power Plant, reducing fossil fuel consumption, reducing dependence and shortening distance to carbon neutrality.

Energy transmission losses are lowered, between bus 1-[...]-4 which before were 55,5% of total losses now are 5,7%. However, this gain, is surpassed by the loss increase between the Wind Power Plant bus 5 and bus 4, now responsible for 76,3% of the grid technical losses.

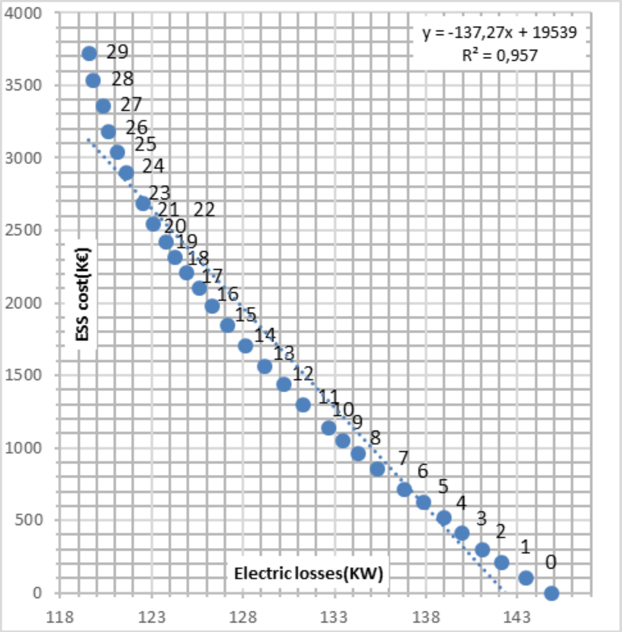


Fig. 12: Secondary population PF, computed by NSGAII for scenario Q3 - 3900kW RES, along with linear regression and correlation.

From Figure 12, we can conclude that the tendency of avoided losses/investment cost ratio continues to decrease. Now the linear regression slope is -137 (Q2.m-118, Q1.m -76,47).

Linear correlation is also an optimization gain indicator, increases in this scenario Q3.r2 0,957 (Q2.r2 0,926; Q1.r2 0,899) which are responsible for lower objectives minimizations, because it reflects a PF with a lower concavity.

For this scenario, it is possible to see in Table 6 that solutions are earlier divided and less centralized on bus 4. Now bus 8 is the third bus with more consumption on the EPS receiving more allocation of ESS, because most of the losses of the branches between buses 4-5 cannot be avoided by a peak shaving dispatch.

In addition, in this scenario using the same method of economic analysis, we can see that the population ratio represents a lower gain for the EPS and a greater demand in investment for the DM. The scenario Q3 population, avoided losses/investment cost is between Q3-N31 6,35W/k€ and Q3-N1 13,43W/k€, being solution Q3-N15 the one with the better balance in both goals (with results in W/k€ near to the Q3 population average).

Table 6. AG computed PF population chromosome matrix and performance for scenario Q 3- 3900kW (1-losses Kw; 2-cost k€).

Bus		1-3	4	5-7	8	9	10-15	P^1	C^2
Solution index	0	0	0	0	0	0	0	144,9	0
	1	0	6	0	0	0	0	143,5	107
	2	0	12	0	0	0	0	142,1	213
	3	0	17	0	0	0	0	141,1	302
	4	0	23	0	0	0	0	140,0	409
	5	0	29	0	0	0	0	139,0	516
	6	0	10	0	25	0	0	137,9	622
	7	0	15	0	25	0	0	136,8	711
	8	0	23	0	25	0	0	135,3	853
	9	0	29	0	25	0	0	134,3	960
	10	0	28	0	31	0	0	133,5	1049
	11	0	33	0	31	0	0	132,7	1138
	12	0	34	0	39	0	0	131,3	1298
	13	0	42	0	39	0	0	130,2	1440
	14	0	34	0	54	0	0	129,2	1565
	15	0	38	0	58	0	0	128,1	1707
	16	0	46	0	58	0	0	127,1	1849
	17	0	46	0	65	0	0	126,3	1974
	18	0	41	0	77	0	0	125,6	2098
	19	0	47	0	77	0	0	124,9	2205
	20	0	53	0	77	0	0	124,3	2311
	21	0	46	0	90	0	0	123,8	2418
	22	0	53	0	90	0	0	123,1	2543
	23	0	61	0	90	0	0	122,5	2685
	24	0	62	0	101	0	0	121,6	2898
	25	0	61	0	110	0	0	121,1	3040
	26	0	67	0	112	0	0	120,7	3183
	27	0	77	0	112	0	0	120,4	3360
	28	0	69	0	130	0	0	119,8	3538
	29	0	79	0	130	0	0	119,6	3716
	30	0	74	0	144	0	0	119,4	3876
	31	0	83	0	144	0	0	119,3	4036

Scenarios (Q1, Q2 and Q3), sensibility analysis

To apply the best solution, the DM should take into account the following: the EPS dispatch protocols, funds available for investment, technological advancement and other aspects.

Making a fast analysis related to the technical-economic goals, based on data used in this paper and considering the DM role, can be assumed that:

- Low power ESS, should be avoided, because they reduce fixed costs compensation (engineering, construction and logistics) and negotiating power;
- ESS solutions with installed power between 1MW to 4MW offer an excellent EPS loss minimization gain, they have a reduced wind energy curtailment avoidance;
- Above 4MW ESS, solutions have a reduced effect on EPS losses mitigation, so they must be excluded.

The analysis should be located between, 1 and 4MW intervals where are the intermediate solutions Q1-N16, Q2-N14 and Q3-N15.

Typical scenarios were developed by quartile and interquartile which divides observed wind space in four. The space above and under the first and third quartile (25%) is overlapped by the space of the third or mean quartile, to compensate that Table 6, shows the “weight” used as a coefficient in the sum of each plot.

Table 6. Coefficient use in Weight Sum, for avoided losses analysis.

Scenario	Q1	Q2	Q3
Coefficient	0,4	0,2	0,4

The solution with the best sensibility gain is solution Q1-N16, as shown in Table 7, using Table 6 coefficient to sum its performance on the complementary scenarios and its main scenario, it´s possible to obtain 28kW, or 23% taking into account the weight sum losses in RES absence that is 119kW.

Table 7. Weight sum and avoided losses sensibility, for intermediate solutions on original and complementary scenarios.

	Scenario	Q1	Q2	Q3	Weight Sum
Avoided losses (kW)	Q1-N16	-50	-22,8	-7,2	28
	Q2-N14	-35,5	-23,3	-14,6	25
	Q3-N15	-30,2	-21,6	-11,7	21

7 Economic Internalities

The Identification of all the variables that may affect the final result is difficult, but it is an aspect that the DM must have in mind.

Having a projected actualization rate of 3,5% (obtained by summing the Cape Verdean low-risk investment interest and inflation) and a 15-year first phase project lifetime, the expected expenses are:

- **ESS acquisition**, which includes engineering, installation and commissioning, with a cost of 450k€ per MW, [36], [37];

- **Maintenance**, to achieve the expected lifetime of the ESS, these should be subject to a maintenance plane. The maintenance plan is divided into fixed maintenance costs and variable maintenance costs. The typical costs are 8,6€/kW and 2,6€/kWh respectively, [36].

The positive cash-flow of the project is given by the following subjects:

- **Carbon credit**, a mechanism that financially supports sustainable development. Avoided CO_2(Ton/MW), an index which is sold by *Caboéolica* for 0,5€/MWh;
- **Energy sold**, stored energy sold price is the same used by *Caboéolica* RES price of 0,15€/kWh.

Yearly it´s expected the usage of 92% of the storage capacity, based on 2018 wind injection in the grid, with a total ESS efficiency of 92% in a complete charge/discharge battery cycle.

In this analysis the DM is *Caboeólica*, with the avoided losses of EPS being a counterpart for *Electra* to receive stored RES that otherwise would be curtailed.

The Profitability study, of both phases results is given in Table 8, using as indicators *pay-back time*, *internal return rate* (IRR) and *net present value* (NPV), [38]; which have low expression a the first investment phase. But in a second phase that relies only on the battery exchange it has a great gain for the DM with an investment value of (135,1k€/MW).

Table 8. Economic indicators result, for ESS investment.

	Phase 1	**Phase 2**
Pay-back	12	1
IRR	282 k€	2.209k€
NPV	5,3%	31,45%

This case study shows how energy tariffs can be reduced, because the RE yearly tariff actualization formula, has a reduction effect based on total RES integration in the archipelago. The ESS based on RES curtailed energy will decrease by 1,74% fossil fuel contribution on the energy tariff.

8 Conclusion

The methodology used in this paper, to model RES curtailment integration, having in mind the economic and technical limitation, can be used as a framework for similar EPS. The initial problem of allocation and sizing ESS on the EPS aims to: minimize of total power losses and minimize of ESS costs.

To solve this multi-objective problem, a GA was applied, whose PF presents a set of distributed solutions that can be used by the DM for practical implementation.

Intuitively, it´s possible to say that the highest consumption buses are the best candidates to allocate ESS, the GA excludes the existence of a small dispersion that may have outweighed this deduction.

Also, the environmental and economic aspect heavily contributes to all interested players in the EPS (*Electra*, *Caboeólic*a and consumers).

Another crucial observation that can be taken from this paper and case study is the importance of integrating more RES combined with ESS on the power grid and its direct relation with its strong contribution to global "carbon neutrality" and energy efficiency. These two technologies should be intrinsically linked because RES are characterized as being intermittent and not dispatchable. The symbiosis between RES and ESS allows RES to be used with better performance, making better use of the energy generated by them, avoiding wasted energy, when these technologies are operating in over power production (excess of production faced with low load demand). This way it´s possible to allocate renewable energy production stored in ESS to be used in periods of greater consumption or absence of renewable production avoiding the operation of fossil fuel technologies and all their economic and Environmental externalities.

This methodology and its implementation in a real case study, shows how the use of a mathematical tool can be useful as a decision support for EPS DM's. In future this decision support system may be integrated in in a non-radial Islands Power Grid or in a wider Grid of a continental country divided in Virtual Power Plant´s Active Power Grids.

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